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Disclaimer

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Abstract

Absolute Kα line spectroscopy is proposed to study laser-plasma interactions taking place in the Au cone-guided fast ignition targets. X-ray spectra ranging from 20 to 100 keV were quantitatively measured with the Laue spectrometer composed of a cylindrically curved crystal and a filter-absorption method for Bremsstrahlung continuum emission. The absolute sensitivities of the Laue spectrometer systems were calibrated using pre-characterized laser-produced x-ray sources and radioisotopes. The integrated reflectivity for the crystal is in good agreement with predictions by an open code for x-ray diffraction. The calibration results show good agreement with theoretical predictions. The energy transfer efficiency from incident laser beams to hot electrons, as the energy transfer agency, is derived as a consequence of this work. The absolute yield of Au and Ta Kα line was measured in the fast ignition experimental campaign performed at Institute of Laser Engineering, Osaka University. Applying the hot electron spectrum information from electron spectrometer or scaling laws, energy transfer efficiency of incident LFEX, a kJ-class PW laser, to hot electrons was derived for the first time.

Keywords: X-ray spectroscopy, Lasere-plasma interaction, Hard x-rays, Fast Ignition

1. Introduction

Fast ignition is recognized as a promising pathway to efficient thermonuclear fusion in laser-driven inertial confinement fusion. A cone-guided CD-shell has been used as a base-line target for the fast ignition experiment [1]. It has long been expected to provide more quantitative information about the hot electron generation and transport in the cone than those derived only with x-ray imaging and neutron detection. In this research, we propose an absolute Kα line spectroscopy dedicated for quantitative measurement of hot electron generation and transport in the high-Z target. This diagnostic provides local information about the hot electrons propagating through specific materials composing the cone-guided target.

In this study, Au and Ta were chosen as tracer since they are representative highest-Z materials which are available for the guide cone, thus better matching with MeV-hot electrons than lower-Z tracers such as Cu.

2. High energy Kα x-ray spectrometer

A Laue spectrometer was developed to cover high energy range from Mo (Kα_1: 17.48 keV, Kα_2: 17.37 keV) to Au (Kα_1: 68.80 keV, Kα_2: 66.99 keV) Kα lines. As shown in Fig. 1, the spectrometer consists of a cylindrically curved Quartz (10-11) plate of 0.2 mm in thickness, 14 mm in height and 30 mm in width (direction corresponding to spectral dispersion). The detector can either be an imaging plate (IP) from Fuji film [2] or a charge coupled device (CCD: Andor Model DH420-FO, 6.7 mm in height and 25 mm in width) with a fiber-optic plate coated with a CsI phosphor of 100 μm in thickness. The Quartz plate is bent with a radius of 170 mm in such that the diffracted x-rays are focused once at the intermediate slit. X-ray components propagating in a straightforward manner are prohibited irradiating the detector directly with a lead pinhole plate located in front of the crystal and a pair of lead shields located at the intermediate x-ray focus. To avoid influence of hard x-rays from plasma on output signal, whole body of the spectrometer and the detector are covered with lead shields. This Cauchois geometry effectively discriminates 0^{th} order component, stray x-rays and fluorescence from spectrometer components such as filters [3, 4]. By varying the distances from the crystal to the source and detector, this spectrometer can cover the energy range of either 10-60 keV (Type-I set) or 30-100 keV (Type-II set) (see Fig. 1 for details).

Absolute sensitivity of the Laue spectrometer was defined as follows. Firstly, the overall sensitivity was calibrated using laser-produced-plasma (LPP) Kα lines and radioisotopes (RIs).

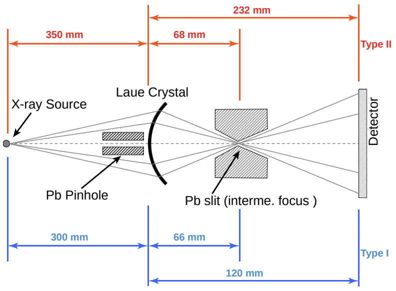

Figure 1: Experimental setup.

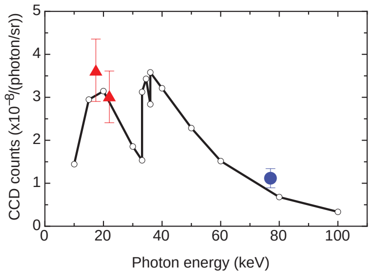

Figure 2: Overall sensitivity of Laue spectrometer system with CsI/CCD detector. The solid line represents a product of spectral sensitivities for the crystal and CsI/CCD. Experimental data points are also plotted for comparison.

For RIs, IP was used in place of the CsI/CCD because of the low-yield-rate of x-rays. Cross-calibration between the IPs and the CsI/CCD was performed at discrete energies. Secondly, to fully span the energy range, the spectral responses of the individual components of the spectrometer were theoretically calculated and compared to the experimental calibration data [5].

Absolute sensitivity for the Type-I set was measured [6] at J-KAREN laser system at Japan Atomic Energy Agency, Kansai Photon Science Institute [7]. This system delivers a laser pulse of 800 nm in wavelength, 1.8 J in energy and 58 fs in duration. The pulse contrast ratio was typically 10^{-11}. An f/2.67 gold-coated off-axis parabolic mirror was used to focus a p-polarized laser beam at an incident angle of 22.5° relative to the target normal. 100-μm-thick Mo and Ag plate targets were mounted on a motorized translation stage. The laser focal spot size was varied with translating the target along the laser beam to change laser irradiance intensity while keep the energy consistent. Absolute yield of Kα x-rays was measured with a pre-calibrated back-illuminated x-ray CCD operated in a single-photon counting mode. The calibration for the Type-II was taken out with radioisotopes. The line emission at 59 keV from ^{241}Am (370 kBq), and 77 keV from ^{226}Ra (3.7 MBq) were used. The calibration with ^{226}Ra was taken out at the OCTAVIAN facility at Osaka University. Due to a long exposure time, IP of Type BAS-TR2025 from Fujifilm was applied in place os CSI/CCD detector [2]. The typical exposure time was 20 to 140 hours. Due to the self-fading effect of IP, the spectral intensities recorded on IP are not in proportion to the exposure time. The absolute sensitivity and fading rate were calibrated in a time range from 5 min to 200 hrs by using the Fuji BAS 1800 IP scanner. The calibration was done at 59 keV by using ^{241}Am; for other photon energy, the data in Ref. [8] is considered. In order to compare the data recorded with CsI/CCD in the experiment, a cross calibration between IP and CsI/CCD has also been made separately.

Diffraction efficiency for the Quartz crystal was derived with XOP code [9] assuming the Takagi-Taupin model [10], and the spectral sensitivity for the CsI phosphor screen was referred from Ref. [11]. Figure 2 shows the comparison result. The solid line represents the product of calculated diffraction efficiency and spectral sensitivity of CsI. Absolute sensitivities calibrated with laser produced Kα lines and that for a radioisotope are respectively shown with triangles and a circle.

3. Kα line measurement and transfer efficiency estimation from fast ignition plasma

The absolute yield of Au Kα line was measured in the fast ignition experimental campaign by using Gekko XII and LFEX lasers at Institute of Laser Engineering, Osaka University [12]. There were three kinds of targets measured, as shown in Fig. 3: Au plate, Au-cone with a CD shell, and Au-cone with CD hemi-shell attached on to a Ta plate.

The transfer efficiency estimation was based on the model of Kα yield from hot electrons [13, 14]:

$$\eta_{K\alpha} = \frac{\eta_{TE}\, n_A\, \omega_{K\alpha}\, E_{K\alpha}}{4\,\pi\, T_h} \int_0^{\infty} dE\, \sigma_{K\alpha}(E) \times \int_0^{d} dx\, f_h(E_0, x)\, exp(-\frac{x}{\lambda_{mfp}\, cos(\theta)}) \quad , \tag{1}$$

where $\sigma_{K\alpha}$, $\omega_{K\alpha}$, and n$_A$ are, respectively, the cross section for K-shell ionization,[15] the Kα fluorescence yield,[16] and the atomic number density. $E_{K\alpha}$ and E are the energy of Kα photons hot electrons respectively. The term $exp(-\frac{x}{\lambda_{mfp}\, cos(\theta)})$ describes the reabsorption of Kα photons during the propagation through the target material where θ is the angle between the spectrometer and target normals. By assuming a single or double temperature Maxwellian function, the hot electron energy distribution function $f_h(E)$ in Eq. (2) is

$$f_h(E) = \frac{1}{T_{h1}} exp(-\frac{E}{T_{h1}}) \times A + \frac{1}{T_{h2}} exp(-\frac{E}{T_{h2}}) \times B \quad . \tag{2}$$

where A and B represent the number fraction of hot electron with temperature T_{h1} and T_{h2}. In this work, the Kα conversion efficiency (η_{K_α}) was absolutely measured by the Laue spectrometer and hot electron distribution function (f_h) was derived from electron spectrometer (ESM) or scaling laws.

3.1. Au plate

The Au plate of 1 mm thickness was irradiated with LFEX laser at the incident angle of 10°. Laser energy on target was varied from 300 to 1700 J on target to achieve irradiance ranging from 6×10^{18} to 1.2×10^{19} W/cm^2. The Laue spectrometer was located in front of the target at 20° from the target normal. Typical Au Kα and Kβ line spectrum is shown in Fig. 4. The 1st order diffraction lines were observed symmetrically on both

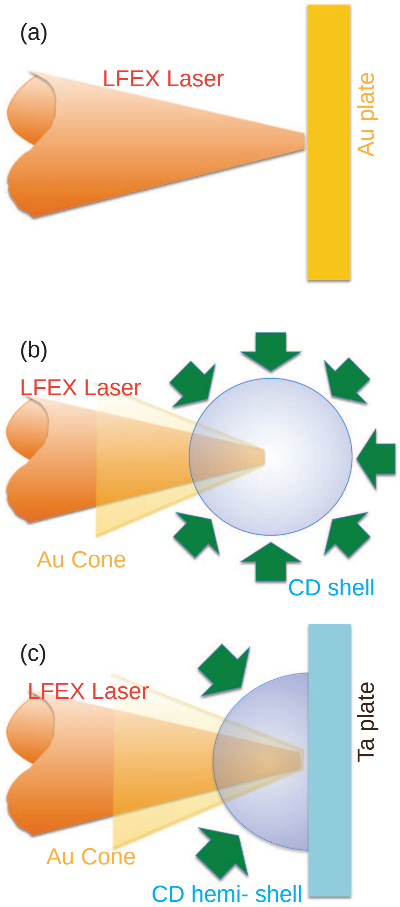

Figure 3: Three kinds of targets: (a) Au plate, (b) Au cone+CD shell, and (c) Au cone+CD hemi-shell+Ta plate.

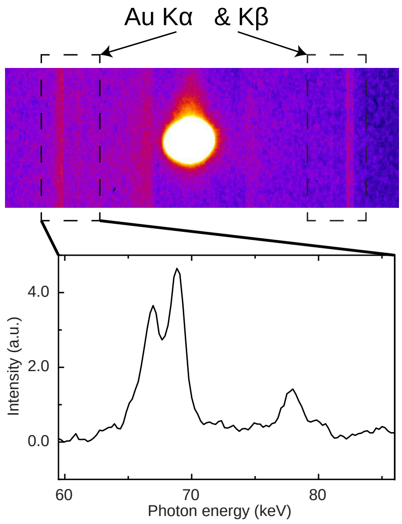

Figure 4: The Au Kα and Kβ lines from the Au plate target. The bright spot on the center in the upper image is the 0^{th} order pinhole image.

Table 1: The intensity, f_h, and η_{K_α}.

Intensity (W/cm^2)	f_h		$\eta_{K_\alpha}(/sr)$
6.1×10^{18}	0.5 MeV	97%	2.2×10^{-6}
	5 MeV	3%	
7.1×10^{18}	0.8 MeV	97%	2.9×10^{-6}
	6.5 MeV	3%	
9.1×10^{18}	1.5 MeV	88%	1.7×10^{-6}
	10.5 MeV	12%	
1.0×10^{19}	1.5 MeV	67%	2.5×10^{-6}
	13 MeV	33%	
1.2×10^{19}	1.8 MeV	73%	3.1×10^{-6}
	16 MeV	27%	

sides, and the bright spot on the center is the 0^{th} order pinhole image. The f_h in this experiment was measured by the ESM. For all the applied laser intensities, a double-temperature structure of hot electron energy distribution was observed. It is worth to note that the lower T_h can be well fitted with Ponderomotive or Beg's experimental scaling laws [17]. The measured η_{K_α} and f_h are summarized in Tab. 1.

The estimated η_{TE} is plotted as a function of the laser intensity in Fig. 5. It is observed that the η_{TE} monotonically increases with increase on the laser intensity, and it ranges from 6% to 15%. A general trend of η_{TE} increasing with laser intensity is observed, and the η_{TE} from LFEX laser to plate target is from 6% to 15%.

3.2. Au cone+CD shell

The second target was an Au-cone CD shell. The thickness of the sidewall and the tip of the cone was 10 μm. CD shell was typically 500 m in diameter and 7 m in thickness. The shell was driven with nine green-laser-pulses from GXII of 1.2 ns in duration and 2 kJ in total energy on target. LFEX laser irradiated the inner wall of the cone tip at the maximum compression of

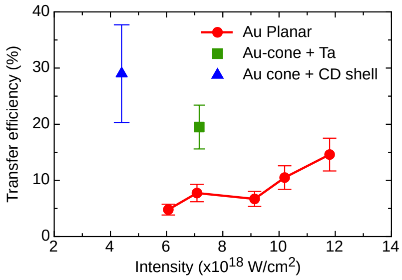

Figure 5: The η_{TE} as a function of the laser intensity for three different kinds of targets.

the shell. Energy and duration of the LFEX pulse were respectively 100-500 J and 1.5 ps, yielding intensity of 10^{18} – 10^{19} W/cm^2 at the cone tip. The density of the core is estimated to be around 10 g/cm^3 and density-radius product is around 0.02 g/cm^2. The Kα line from the Au cone was measured by the Laue spectrometer. The signal intensity was much weaker than the case of Au plate target because of the thickness of the Au layer is much thinner. In this experiment, it was hard to observe clearly data of electron spectrum from ESM, so the T_h was derived from Ponderomotive and Beg's scaling laws [17]. The η_{TE} from the LFEX laser to the Au cone is about 22% to 36%. The uncertainty of T_h leads a large error bar of the estimated η_{TE}, as shown in Fig. 5.

3.3. Au cone+CD hemi-shall+Ta

In order to increase the Kα signal intensity, we have modified the Au cone+CD shell target. The CD shell is replaced with a hemi-shell and a Ta plate of 1 mm in thickness was attached, as shown in Fig .3(c). Three beams of GXII laser were used to compress the hemi-shell. A double-temperature of hot electron energy distribution was observed from ESM, which is similar with the Au plate case. The η_{TE} was estimated to be about 20%.

4. Conclusion

Kα line spectroscopy, particularly for hard-x-ray region, has been proposed for quantitative measurement of cone-guided fast ignition targets. The Au and Ta Kα line from the Au-cone guided target was observed and energy transfer efficiency was provided as a preliminary study. Compared with the planar geometry, the LFEX laser transfer efficiency is significantly enhanced with a Au-cone. In near future, absolute measurement of hard x-ray continuum will be made together with that of the Kα line to improve accuracy of energy transfer measurements in the cone-guided fast ignition targets. Furthermore, detailed analysis with a hybrid modeling, namely combination of particle-in-cell (PIC) code and hydrodynamic code, will be made for Kα yield to improve understanding of hot electron generation, transport and energy deposition in the cone-guided target.

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